

Breaking of Zonal Uniformity in the Tropical Atlantic Decadal Variability

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[1] Simple atmosphere-ocean coupled models are used to study the role of ocean dynamics in the tropical Atlantic decadal variability. Perturbing the model tropical Atlantic from the mid-latitudes with a decadal frequency, inter-hemispheric dipole mode emerges. Near the equator, the cross-equatorial gyre circulation that develops due to the dipole-induced wind stress curl, produces a zonally non-uniform cross-equatorial heat transport (from the cold to warm hemisphere in the western boundary and vice-versa in the interior) that causes a positive zonal SST gradient along the equator. Later, Bjerknes-type feedback kicks in, strengthening the SST gradient. Eventually, this feature grows to a stationary stage sustaining the uplift (depression) of the equatorial thermocline in the west (east), and westerly wind anomalies, a condition similar to Atlantic-Niño. This result suggests that a strengthening of the dipole mode corresponds to a weakening of the equatorial circulation system, consistent with the mid-1970's climate shift reported in earlier studies.

1. Introduction

[2] Unlike the tropical Pacific, climatic fluctuations over the tropical Atlantic are largely forced by perturbations of remote origins, such as ENSO and North Atlantic Oscillation [NAO] [*e.g.*, *Enfield and Mayer*, 1997]. Although weak, two internal modes still hold in the tropical Atlantic variability, namely Atlantic-Niño and dipole modes (a preferable terminology for the latter is Atlantic meridional mode, but here we use these terms interchangeably). The first mode is analogous to ENSO in the Pacific thus prevails at the interannual time scale, but requires external perturbations to sustain finite-amplitude oscillations [Zebiak, 1993]. The second mode is, on the other hand, dominant at the decadal time scale and the associated sea surface temperature anomaly is most pronounced off the equator around 10-15° latitude band [*Chang et al.*, 1997; *Xie*, 1999]. Previous modeling and observational studies [*e.g.*, *Nobre and Shukla*, 1996; *Chang et al.* 1997; *Xie*, 1999; *Enfield et al.* 1999] collectively suggest that the Atlantic dipole mode can emerge through Wind-Evaporation-SST (WES) feedback [*Xie and Philander*, 1994], but since it is weakly damped (*ie.*, not self-sustainable), it is critically dependent upon the mid-latitude forcing patterns, thus anti-symmetric configurations of sea surface temperature anomaly are not ubiquitous in the tropical Atlantic. But even in the absence of inter-hemispheric SST anti-correlation, significant cross-equatorial SST gradients occur much frequently (about 50% of the time during 1856-1991 according to *Enfield et al.* 1999) and can be associated with climate departures [*Wang*, 2002]. Indeed, a recent coupled General Circulation Model (CGCM) study by *Huang and Shukla* [2005] shows that the WES feedback can prevail in non-dipole configurations, causing mid-latitudinal disturbances to propagate equatorward in agreement with idealized model studies [*Xie*, 1997].

[3] It has been suggested that the role of the tropical ocean dynamics is rather passive and does not have a major impact in the tropical Atlantic variability [e.g., *Carton et al.* 1996; *Seager et al.* 2001; *Chang et al.*, 2003; *Joyce et al.* 2004; *Chang*, 2005]. *Servain et al.* [1999; 2000], on the other hand, propose an argument that contradicts the notion that ocean dynamics merely play a damping role in the tropical Atlantic variability. Using historical subsurface data obtained from XBT (expendable bathythermograph) drops, *Servain et al.* [1999] report that a significant correlation exists between the two tropical Atlantic modes during 1979-93. By confirming this through an Ocean General Circulation Model (OGCM) simulation, *Servain et al.* [2000] further propose that equatorial ocean dynamics may be the principal cause of the tropical Atlantic climate variability at the interannual timescale (by latitudinal displacement of the ITCZ). *Murtugudde et al.* [2001] present a supportive modeling result adding that the 1976 ‘climate shift’ [*Trenberth, 1990*] also occurred in the tropical Atlantic and that the main mode of SST variability shifted from meridional to zonal mode. They further speculated that changes in ENSO frequency before and after 1976 are responsible for the dominant-mode shifting in the tropical Atlantic.

[4] The focus of this study is to investigate the role of the tropical ocean dynamics in shaping the tropical Atlantic variability. In particular, we want to test the notion that the tropical ocean is an active player in the tropical Atlantic variability on the decadal timescale by using idealized coupled models. The framework for our modeling study closely follows the simple modeling work of *Xie* [1999]. Here, we revise his idealized coupled model by (1) allowing zonal variations, and (2) replacing the slab ocean model with a fully dynamic 2.5 layer reduced gravity ocean model [*Lee and Csanady*, 1999b].

2. Models

[5] The original *Gill* [1980] model is used for the atmosphere. The model parameter values are chosen to be identical to those used in *Xie* [1999], except for the thermal coupling coefficient and the Newtonian thermal damping coefficient. These values are appropriately chosen to ensure that the simulated WES feedback is weakly damped in the tropical Atlantic model configuration with the intrinsic resonant period at approximately 10 years, as indicated in previous observational and modeling studies.

[6] The ocean model is a simplified version of the 2.5 layer reduced gravity ocean model used in *Lee and Csanady* [1999b]. The entrainment/detrainment rate, w_e , is now parameterized as linearly dependent on the mixed layer depth anomaly, h_1 , *i.e.*, $w_e = -\gamma h_1$, where γ is set to $(365\text{day})^{-1}$. The model Atlantic ocean is a rectangular box, extending zonally from 80°W to 20°E and meridionally from 30°S to 30°N ($\Delta x = \Delta y = 0.7^\circ$). The north and south boundaries are closed with a slip-condition applied at all sidewalls. The mean ocean state is 200m deep ($h_1=100$; $h_2=100$) with the thermal parameters chosen to yield two internal gravity wave speeds of 2.5 and 1.0 m/s, and assumed to be at rest for simplicity. For comparison with our dynamically coupled model runs (Gill-reduced gravity ocean model or simply Gill-rgom hereafter), a slab ocean model is also coupled to the Gill atmospheric model (Gill-slab hereafter). Such models have been used extensively for tropical climate studies [*e.g.*, *Hirst*, 1986], thus the model equations are not repeated here.

[8] In all model runs, a sea surface temperature perturbation is imposed only between 25° and 30° with the forcing period of 10 years, in order to mimicking the decadal low-mid-latitude perturbations typically caused by ENSO and NAO. Coupled model runs are carried out using an anti-symmetric mid-latitude forcing pattern, *i.e.*, the sign of forcing is opposite in the two

hemispheres but with the same amplitude. In the following section, these model runs are used to describe the atmosphere-ocean feedback.

3. Results

[9] Fig. 1a shows the latitude-time structure of the zonally averaged sea surface temperature and wind components simulated by the Gill-slab model under the anti-symmetric mid-latitude forcing. The structure of the solution closely resembles the WES feedback mode studied earlier by *Xie* [1999], showing clearly the SST see-saw pattern north and south of the equator that slowly propagates equatorward, and the cross-equatorial winds blowing from the cold to the warm hemisphere. Fig. 1b is the same as Fig 1a but for the Gill-rgom run. The most striking difference between the two cases is that the amplitude of anomalous signals is much weaker when ocean dynamics are activated (Fig. 1b), suggesting that local ocean dynamics contribute to the damping of Atlantic dipole mode in agreement with earlier studies. The most likely mechanisms for the damping are the inter-hemispheric heat exchange due to ocean dynamics [*Chang et al.* 2001; *Joyce et al.* 2004], and the Ekman-upwelling (downwelling) in the warm (cold) hemisphere. However, it appears that ocean dynamics do more than just damping because the latitude-time structure the solution is also altered. In particular, the location of the nodal point (zero contour lines of SST anomalies) is shifted about 2-3° off the equator toward the cold hemisphere, and the center of the maximum meridional wind anomalies is also shifted accordingly, displaying a meandering pattern.

[10] Fig. 2a and 2b show model solutions during the peaks of SST dipole for the Gill-slab and the Gill-rgom cases, respectively. As shown in Fig. 2a, the anomalous SST and winds are more pronounced toward the west, and this feature appears to originate from westward propagating

WES waves that amplify as they move westward [Xie, 1996]. The zonally near-uniform oscillating structure in the Gill-slab run is nearly collapsed in the Gill-rgom run especially within the equatorial band (Fig. 2b). A positive zonal SST gradient (increase eastward) persists during the entire oscillation period. Relatively weak but persistent westerly anomalies prevail along the central and eastern sides of the equator reinforcing the positive zonal SST gradient there, a Bjerknes-type positive feedback.

[11] Fig. 2c displays oceanic mixed layer depth (h_1) and transport (uh_1 and vh_1) anomalies during the peaks of SST dipole, corresponding to the SST and winds shown in Fig 2b. Close inspections of Fig. 2c along with Fig. 2b suggest that the central mechanism responsible for the breaking of the zonal uniformity of SST dipole is the cross-equatorial oceanic gyre circulation that emerges due to the wind stress curl pattern associated with the inter-hemispheric SST dipole [Joyce *et al.* 2004]. More specifically, the anomalous gyre circulation allows a cross-equatorial transport of the mixed layer water from the warm (cold) to cold (warm) hemisphere in the interior ocean (western boundary), and as a result a positive (negative) SST anomaly persists in the central (western) equatorial Atlantic (see Fig 2b). This equatorial SST anomaly (cold in the west and warm in the central and eastern equatorial Atlantic), in turn, drives westerly wind anomalies, thereby uplifting (depressing) the equatorial thermocline in the west (east). Anomalous entrainment cooling (warming) in the west (east) allows the equatorial SST and wind anomalies to grow stronger, closing the positive feedback loop. Oscillations of the thermocline depth and associated transport anomalies off the equator (not shown) are similar to those simulated by using 1.5 layer ocean model forced with dipole-induced wind stress [Joyce *et al.*, 2004]. Near the equator, however, the eastward equatorial undercurrent anomalies persist during the entire oscillation period (not shown), consistent with the Bjerknes-type feedback.

[12] The longitude-time structure of the equatorial mixed layer depth (not shown) reveals that one or two forcing cycles are required for the zonal pattern to grow to a fully mature stage. Once it reaches its full strength, however, this zonal structure becomes nearly stationary, feeding its energy from the WES feedback that in turn requires decadal perturbations from mid-latitude. Since this zonal pattern produces a condition similar to Atlantic-Niño, it is referred to as “stationary Atlantic-Niño mode”.

4. Summary and Discussions

[15] Simple coupled models are used to investigate how ocean dynamics interact with the atmosphere in tropical Atlantic decadal variability. Our model results suggest that ocean dynamics play an important role by breaking zonal uniformity in the tropical Atlantic variability that is otherwise largely sustained by the meridional SST gradient mode. The central mechanism appears to be the cross-equatorial oceanic gyre circulation that produces a zonally non-uniform cross-equatorial heat transport (from the cold to warm hemisphere in the west and vice versa in the interior), eventually causing a positive zonal SST gradient along the equator (warm in the west and cold in the east). Later, Bjernes-type positive feedback kicks in, thus the zonal SST gradient grows stronger. One or two oscillation cycles are required for this zonal structure to grow to a fully mature stage, sustaining the needed energy from the meridional mode and also the positive atmosphere-ocean feedback mechanism. The outcome is the uplift (depression) of the equatorial thermocline in the west (east), and westerly wind anomalies, a condition similar to Atlantic-Niño, thus named here as “stationary Atlantic-Niño mode”.

[16] Although not shown here, additional experiments with different mid-latitude forcing patterns suggest that the WES feedback mechanism still works under a symmetric mid-latitude

forcing pattern with and without ocean dynamics, but the oscillations are much weaker. Interestingly, the stationary Atlantic-Niño mode that prevails under the anti-symmetric mid-latitude forcing does not exist in this case, suggesting that inter-hemispheric SST contrast is the precondition for generating the stationary Atlantic-Niño mode. In summary, it is important to note that the decadal perturbation from the mid-latitude is the ultimate source of the oscillations, because the meridional mode has the intrinsic resonant period at the decadal timescale and is not self-sustainable. Hence, the stationary Atlantic-Niño mode cannot be evoked without the inter-hemispheric SST contrast, and cannot be excited at the interannual timescale.

[17] Due to the highly idealized nature of our coupled model, it is premature to engage in a model-data comparison at this stage. However, there are some OGCM results that support the existence of decadal changes in the zonal slope of the equatorial Atlantic thermocline [*Murtugudde et al. 2001*]. According to *Murtugudde et al. [2001]*, the zonal slope of the equatorial thermocline is shifted in mid-1970's, from a weak phase (1958 – 1975) to a strong phase (1976-2000). Of course, this may or may not be related to the mechanism described here. However, since the meridional mode was the dominant climate variability before the mid-1970's [*Murtugudde et al. 2001*], the decadal phase shift in equatorial thermocline is consistent with our finding that the excitation of a meridional mode corresponds to the weakened zonal slope of the equatorial thermocline. Although not investigated here explicitly, this decadal shift of the equatorial thermocline may also contribute to the changes in frequency and strength of interannual Atlantic-Niño mode (3 warm events occurred during 1950-1975 and 8 during 1975-2000 according to Wang, 2002).

[18] To validate our findings and conclusions, more studies using observations and CGCMs are needed. However, since the equatorial Atlantic circulation system serves as the important

gateway for the inter-hemispheric mass and heat transport [e.g., *Lee and Csanady*, 1999a], the stationary Atlantic-Niño mode, if exist, may contribute to the weakening of the equatorial Atlantic circulation system and possibly be linked to the basin-scale Atlantic thermohaline circulation.

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Figure captions

Figure 1. Latitude-time structure of the zonally averaged sea surface temperature (top panels in °C) and wind components (zonal wind in the middle and meridional wind in the bottom panels in m/s), simulated by (a) the Gill-slab model and (b) the Gill-rgom model under the anti-symmetric mid-latitude forcing. The contour interval is 0.5 for the sea surface temperature, 0.2 for the zonal wind component and 0.1 for the meridional wind.

Figure 2. Sea surface temperature and wind components at $T=22.5$ (upper panels) and 27.5 (lower panels) yrs simulated by (a) the Gill-slab model and (b) the Gill-rgom model. Shown in (c) are the mixed layer depth and transport anomalies corresponding to (b). The maximum arrow is about 1.5 m/s for (a), 0.9m/s for (b), and $10\text{m}^2/\text{s}$ for (c). The contour interval is 0.5 for (a), 0.25 for (b) and 5 for (c).

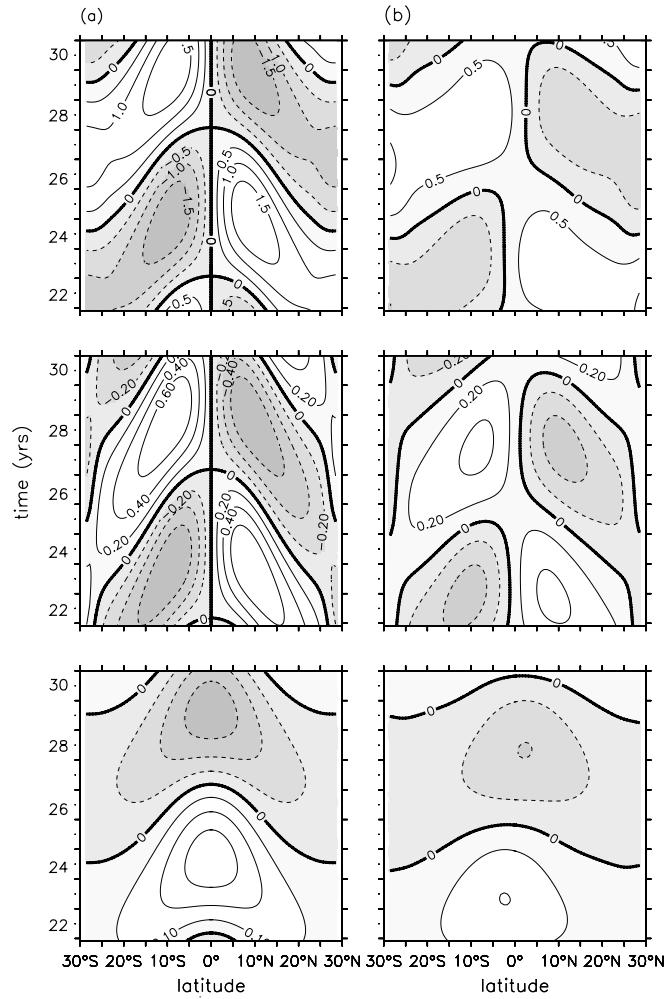


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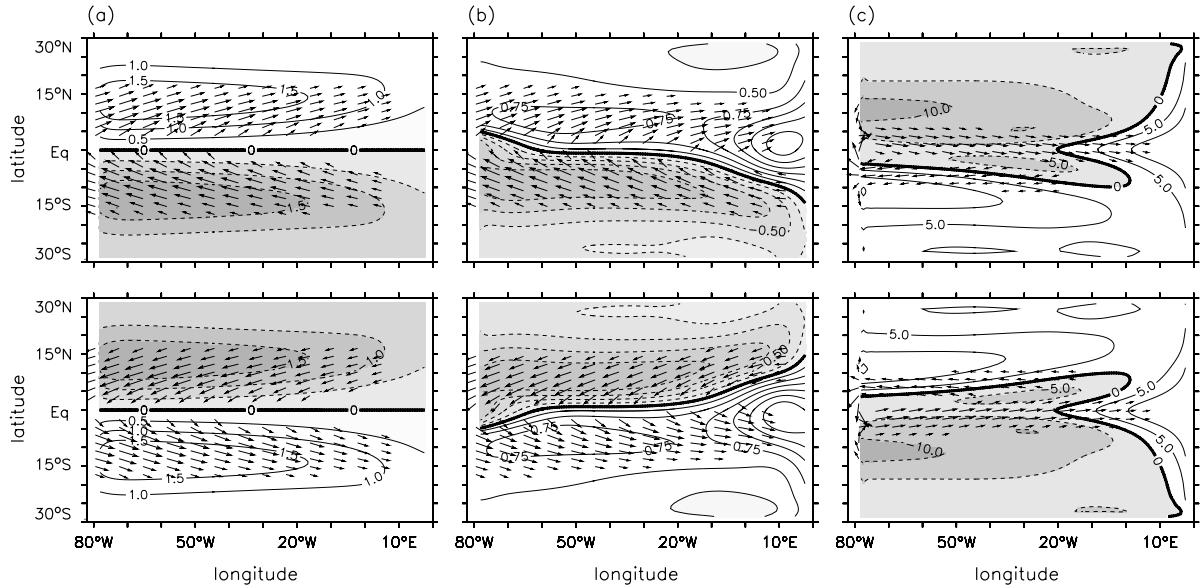


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